Spatial Variation of Wind Stress and Wave Field in the Shoaling Zone

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LONG-TERM GOALS

Existing atmospheric models for predicting surface stress and turbulent structure in the shoaling zone fail because of their inability to properly account for wave age, shoaling, and internal boundary layer development. Accurate model simulation of surface stress and turbulence above the air-sea interface is important for a number of applications including understanding wave growth and decay. Our goals are:

1. to measure the spatial variation of the wind, surface stress, and ocean wave fields in the shoaling zone and to provide quality-controlled data to the shoaling community; and

2. to study the relationship between the spatial varying mean wind, stress, turbulence structures, and surface wave fields in order to model effects of wave age, shoaling, and internal boundary layer development on the drag coefficient and momentum transfer.

OBJECTIVES

The key to achieving our goals is the development of a data archive containing simultaneous observations of the spatially varying wave, wind, and stress fields in the shoaling zone. At the start of this project, instrument systems for making such observations did not exist. Over the last four years, we have achieved our first objective which was to develop and demonstrate an efficient measurement system to measure the spatial variation of the wind, surface stress, and ocean wave fields in the shoaling zone. This report focuses on instrument system development and its application in the Shoaling Waves Experiment (SHOWEX).

APPROACH

The LongEZ (registration N3R) is a pusher-engine research aircraft that has been used extensively to acquire data for a variety of air quality and environmental research projects (Fig. 1). This aircraft has proven to be especially powerful in studying the spatial variability of air-sea exchange. The instrument

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suite and data acquisition system are used to measure mean properties of the atmosphere as well as turbulent fluxes of heat, moisture, and momentum. Remote sensors (laser altimeters and a Ka-band scatterometer) were added to determine wave field properties of the ocean such as wave height, roughness, phase speed, and directional spectra.

Fig. 1. LongEZ N3R in front of the Wright Brothers National Memorial at First Flight Airport in Kill Devil Hills, NC.

The “Best” Aircraft Turbulence (BAT) probe was developed by scientists and engineers from NOAA’s Air Resources Laboratory and Airborne Research Australia. The BAT housing consists of a 15-cm diameter carbon-fiber hemisphere mounted on a tapered cone which is mounted on the nose of the aircraft. The housing contains solid-state pressure sensors used to measure differential and static pressure from pressure ports on the hemisphere. These measurements provide the pressure distribution over the hemisphere from which the air relative velocity may be computed. Ground relative velocities are provided by differentially-corrected GPS which provides three-dimensional velocity with an accuracy of roughly 4 to 5 cm s^{-1}. High frequency measurements are made from three orthogonally-mounted accelerometers. These devices are used to augment GPS data to 50 Hz. Wind velocities are derived by taking the difference between vectors of air and ground relative velocity. Aircraft attitude (pitch, roll, heading) is measured using a Trimble Advanced Navigation System (TANS) vector GPS. The TANS consists of four antennas mounted on the BAT probe housing, wings, and rear of the cockpit. Using carrier-phase interferometry, the position of three antennas is measured relative to a master antenna.

Air temperature measurements are acquired by redundant fast-response micro-bead thermistors. A NOAA-designed open-path infrared gas analyzer measures turbulent fluctuations in water vapor and carbon dioxide at frequencies. Three sets of radiometric sensors measure both upwelling and downwelling radiation. A Radiation and Energy Balance Systems radiometer provides measurements of net (long and shortwave) radiation. Upward looking and downward looking Li-Cor photosynthetically active radiation (PAR) sensors measure the incoming and reflected portion of the visible solar spectrum. Upward and downward looking Everest Interscience infrared radiometers are used to measure sky and surface temperature.

A laser altimeter array and a NASA-designed 36-GHz (Ka-band) scatterometer were used to determine long and short surface wave characteristics, respectively. The data obtained from these remote sensors provide wave information from small capillary waves to long swells coupled with in situ measurements of wind stress and turbulence. An array of three Riegl laser range finders were used to determine ocean wave characteristics such as wave height, roughness, phase speed, and directional spectra. The laser array consists of three downward looking lasers mounted on the vertices of a 1-m equilateral triangle. Two are mounted under either wing while the third is mounted in an instrument pod below the aircraft fuselage. The lasers operate at a pulse repetition frequency of approximately 2 KHz. Thirty-eight individual pulses are averaged down to a rate of 50 Hz to reduce noise. The focal length of the lasers was set to 15 m providing a nominal accuracy of ±2 mm. With a typical flight speed of 50 m s^{-1}, the laser array can be used to determine wave characteristics for wavelengths greater than 5 to 6 m. The low-power nadir-pointing scatterometer is also mounted in the instrument pod. This sensor is used to infer short wave characteristics by relating backscatter intensity to the mean-square slope (variance) over wave scales from 0.01 to 1 m. Coincident laser altimeter measurements provide the precise range information for computation of the normalized radar cross section. Visual and infrared images of whitecaps were acquired by the Modular Aerial Sensing System (MASS) developed by Ken Melville (SIO). Such measurements, when combined with knowledge of aircraft velocity, are used to determine the temporal evolution of breaking waves. The MASS sensors were mounted in the rear portion of the instrument pod. A schematic of the LongEZ and its instrumentation are shown in Fig. 2.

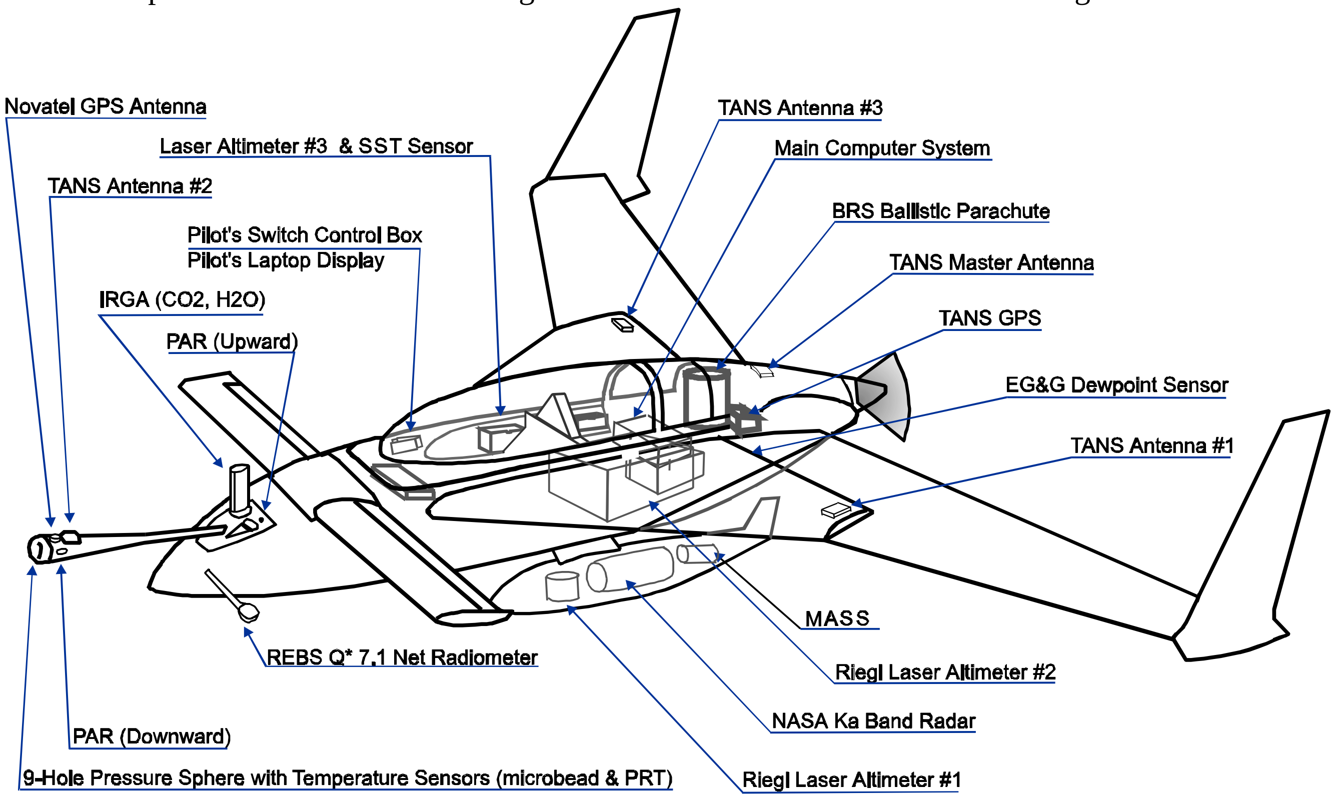

Fig. 2. Configuration of the various instrument systems on LongEZ N3R used for SHOWEX.

WORK COMPLETED

Twenty-seven missions (105 flight hours) were conducted from 11 NOV to 05 DEC 1999 under various atmospheric and wave field conditions during the SHOWEX intensive observation period. Many of the flights were conducted in the vicinity of the U. S. Army Field Research Facility in Duck, NC. In order to assess changes in atmospheric turbulence and the ocean wave field through the shoaling region, repeated transects were flown both perpendicular and parallel to the coastline at various altitudes. Soundings were also conducted during each flight to assess the vertical structure of the marine atmospheric boundary layer.

RESULTS

The following example is based on low-level (~ 10 m) east-west transits from the Outer Banks of North Carolina to the edge of the Gulf Stream on 20 NOV 99 (Table 1). Six legs were flown over the same track during the course of the flight. The region was dominated by a high pressure system located off the Nova Scotia coastline. Horizontal surface pressure gradients were generally weak and skies were clear. In general, observed winds were from the south to southwest with speeds ranging from near calm to about 4 m s^{-1}. Near the edge of the Gulf Stream, wind speeds generally increased and were in the range of 5 to 8 m s^{-1}. Relatively smooth seas were observed near the coast. Using eddy correlation techniques, turbulent parameters were computed from 50-Hz data as discrete 60-s blocks (~ 3 km). These parameters display some variability in the shoaling zone. From 10 km out to about 60 to 70 km, these turbulent parameters are generally uniform. Near the edge of the Gulf Stream, however, the atmospheric boundary layer became unstable with a positive temperature difference (sea surface minus air) and negative stability z/L (L is the Monin-Obukhov length). In the shoaling zone and near the Gulf Stream, variability in friction velocity u_* and drag coefficient C_D are observed. Scatter plots (Fig. 3) of u_* and C_D are shown as a function of 10-m wind speed U_{10} and z/L. Considerable scatter is observed in these plots. One interesting feature is seen when U_{10} is less than 2 m s^{-1}. Most of these points were observed near the end of Leg 1 near the beginning of the flight. In this case, C_D appears to be inversely proportional to U_{10}. It should be pointed out, however, that there is much disagreement in research findings of how C_D behaves under light wind regimes.

Table 1. Low-level flux legs acquired by the LongEZ during SHOWEX on 20 November 1999.

Leg	Key	Start (UTC)	End (UTC)	Duration (MM:SS)	Distance (km)	Heading ± 1σ (deg)	Z ± 1σ (m)
1	●	14:04:35	14:34:55	30:20	97.4	103 ± 4.4	9.9 ± 2.2
2	●	15:46:54	16:14:06	27:12	92.6	278 ± 2.4	7.7 ± 2.2
3	●	16:20:23	16:57:00	36:37	114.7	104 ± 5.2	7.3 ± 2.1
4	●	16:58:25	17:32:08	33:43	112.9	277 ± 3.0	8.2 ± 2.1
5	●	17:34:08	18:09:33	35:25	113.9	103 ± 2.6	6.4 ± 2.7
6	●	18:10:56	18:43:53	32:57	111.9	279 ± 3.4	7.0 ± 1.8

IMPACT / APPLICATIONS

The atmospheric and sea surface data acquired from the SHOWEX pilot studies in November 1997 and March 1999, and the SHOWEX intensive observation period are being used to address spatial variability of the wind, surface stress, and ocean wave fields in the shoaling zone. These data suggest parameters such as drag coefficient, are strongly dependent upon wind direction (i.e., onshore versus offshore), atmospheric stability, and wave state. These data will be used to better refine model parameterizations in coupled air-sea models.

Data from this remote sensing system package are being used to reduce the uncertainty in the electromagnetic range bias that corrupts satellite sea surface topography measurements. The NASA-funded Wave Profile Experiment (WAPEX) will examine these data to refine EM bias models for large-scale tilt, short-scale diffraction, and hydrodynamic effects. Our approach to measure surface wave characteristics using a laser altimeter array and Ka-band scatterometer has been successful and is being adapted by other researchers. This remote sensing system is being refined by adding a microstrip Ku-band (2.3 cm) nadir-viewing scatterometer to operate alongside the Ka-band system expressly for support of the light wind observations. Under these conditions, we anticipate a wave environment characterized by 5 - 15 cm scale carrier waves having parasitic capillary waves governing their growth. Recent dual-frequency TOPEX altimeter satellite studies have shown that this scatterometer combination provides a useful tool for probing these characteristics for light winds.

TRANSITIONS

Data from the SHOWEX pilot study (March 1999) and the intensive study (November - December 1999) is being cooperatively analyzed by colleagues Douglas C. Vandemark, Jielun Sun, Larry Mahrt, Pierre D. Mourad, and W. Kendall Melville. In particular, data acquired on days with a light wind-regime are carefully being analyzed in preparation for the ONR-sponsored Coupled Boundary Layer Air-Sea Transfer (CBLAST) Departmental Research Initiative (DRI).

RELATED PROJECTS

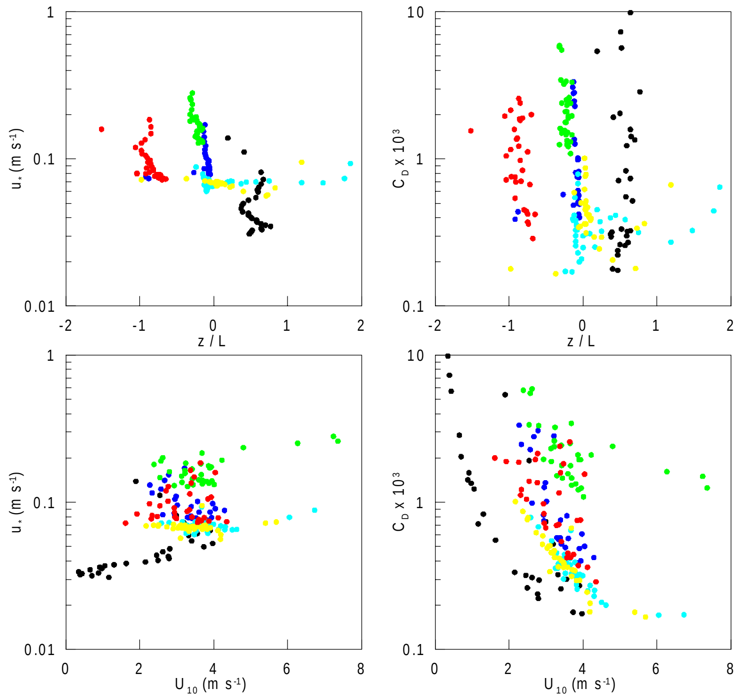

Fig. 3. Scatter plots of u_* and C_D versus U_{10} and z/L.

Although funded separately, this project is a cooperative effort with D. C. Vandemark (radar development and analysis, N00014-97-F-0179), J. Sun (data interpretation, N00014-98-1-0245), L. Mahrt (data interpretation, N00014-97-1-0279), P. D. Mourad (SAR intercomparisons, N00014-97-1-0278), and W. K. Melville (wave breaking).

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